Liquid Crystal Technology for Adaptive Optics: un update

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ABSTRACT

The idea of using liquid crystal devices as an adaptive optics component has been proposed by several authors. In recent years a vigorous research effort has been carried out, and it is still flourishing, in several countries. Mainly the research and experimental work has been concentrated in the USA, U.K. and Russia. There are several reasons why liquid crystals may represent a valid alternative to the traditional deformable mirror technology that has been used for the past two decades or so. The main attractiveness of LC resides in the cost. Current deformable mirror technology has a range of price going from $2K to $15K per channel. LC technology promises to be at least a couple of orders of magnitude cheaper. Other reasons are connected with reliability, low power consumption and with a huge technological momentum based on a wide variety of industrial applications. In this paper we present some preliminary characterizations of a new, large format device. Such devices have the potential for extremely high-resolution wave-front control due to the over 10,000 corrective elements. The characterization of the device, so far, consists of measurements of the overall optical quality and of the phase control relationship.

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The idea of using liquid crystal devices as an adaptive optics component has been proposed by several authors. In recent years a vigorous research effort has been carried out, and it is still flourishing, in several countries. Mainly the research and experimental work has been concentrated in the USA, U.K. and Russia. There are several reasons why liquid crystals may represent a valid alternative to the traditional deformable mirror technology that has been used for the past two decades or so. The main attractiveness of LC resides in the cost. Current deformable mirror technology has a range of price going from $2K to $15K per channel. LC technology promises to be at least a couple of orders of magnitude cheaper. Other reasons are connected with reliability, low power consumption and with a huge technological momentum based on a wide variety of industrial applications. In this paper we present some preliminary characterizations of a new, large format device. Such devices have the potential for extremely high-resolution wave-front control due to the over 10,000 corrective elements. The characterization of the device, so far, consists of measurements of the overall optical quality and of the phase control relationship.</td></tr>
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1. Introduction

In the past few years several groups have been actively engaged in demonstrating the use of liquid crystal (LC) devices for wavefront shaping and control. The focal points of these groups are in USA [1-7], Europe [8-12], and Japan [13]. The reasons behind the use of LC for wavefront control are several. First of all is cost: the main technological push is based on the display industry, which has invested a large amount of money in developing materials, techniques and hardware that can be modified and adapted to be used for wavefront control applications. Other reasons include the low power consumption, low weight, compactness of the devices, and the fact that these are non-mechanical devices with very high lifetime.

However, there are also some drawbacks. In using *nematic* materials the main problems are: polarization dependence and low temporal bandwidth. The first problem was solved by our group through the Small Business Innovative Research (SBIR) program in conjunction with Meadowlark Optics [14]. The second problem has also been solved through a SBIR with Meadowlark [15].

In an adaptive optics system one is adjusting the optical path (OP) of the incoming wavefront. When using a deformable mirror or liquid crystal device such adjustments can be done in two ways since the OP is the product of two quantities

$$OP = \Delta z \cdot n \quad . \qquad [1]$$

Where Δz is the geometrical path and n is the refractive index of the medium. A conventional deformable mirror (DM) will modulate Δz, while a liquid crystal device will modulate n.

Since nematic materials are birefringent the modulation of the refractive index happens only for one of the polarization states. One way to obviate this problem is to manufacture a device with two orthogonal layers of the same LC material[3].

The phase modulation that can be induced by an LC cell is given by

$$\Delta\phi = \frac{2\pi}{\lambda}\int_{-d/2}^{d/2}[n(z) - n_{\perp}]dz + \langle\Delta\Phi\rangle \quad . \qquad [2]$$

Here $n_{\perp}$ is the extraordinary component of the refractive index, d is the thickness of the cell and $\langle\Delta\Phi\rangle$ is the phase component due to thermal fluctuations etc. This last term is usually negligible, for room temperature and standard thickness. For the material used in this experiment; this term is usually of the order of 10^{-7} radians. Detailed derivation of the expression for $\langle\Delta\Phi\rangle$ can be found in Ref. [15]. From eq. 2 it is possible to see that the amount of phase modulation depends on the thickness of the cell. However, the thicker a cell is, the slower will be its response time. A trade-off between these two parameters has to be found. Another way around the limitation of the bandwidth is to use different types of LC materials. Additionally, LC devices offer the capability of having a very large format and a high density of correction elements. In this paper we present a preliminary characterization of such a device. The physical characteristics of this device are shown in Table 1.

Table 1: LC Properties

Thickness of the cell :	10 μm
Liquid Crystal Material :	Rodic RDK-01160
Birefringency (Δn):	0.20 [25 ^{0}C and λ=589 nm]
Configuration :	π cell
Clearing point :	94 ^{0}C
Melting point:	-25 ^{0}C

2. Wavefront quality measurements.

The device that we are evaluating here was developed by Boulder Nonlinear Systems (BNS) under an SBIR. The device, shown in Fig.1, is 13X13 cm^2 in area with 128X128 corrective elements.

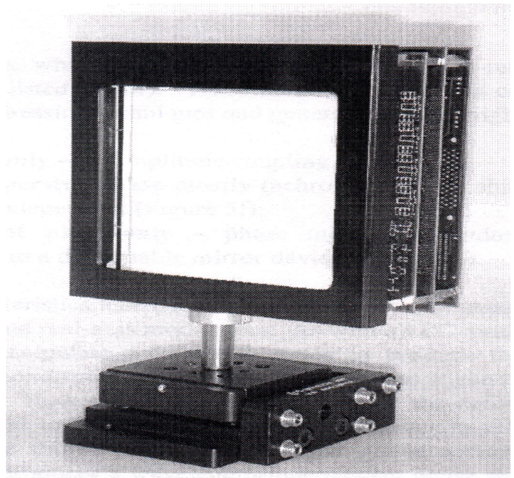


Figure 1: Image of the device

The device is a reflective device with a silicon back-plane, one advantage of this is that some of the support electronics for the device have been manufactured on this reflective structure. The first step in the characterization of the device was to measure the quality of the reflected wavefront from the backplane alone. This was accomplished by using a Zygo interferometer with a beam width of approximately 5”. The result is shown in Fig. 2. The scale of the mesh-plot in Fig . 2. is in waves and the peak-to-valley error is $\lambda/13$. Note in Fig.2 the imprints on the wavefront due to the electric lines to carry the signal to the individual pixels. It was decided that the best addressing scheme for this device was a passive matrix scheme. This, among other reasons, minimizes the electric line imprints on the surface of the backplane.

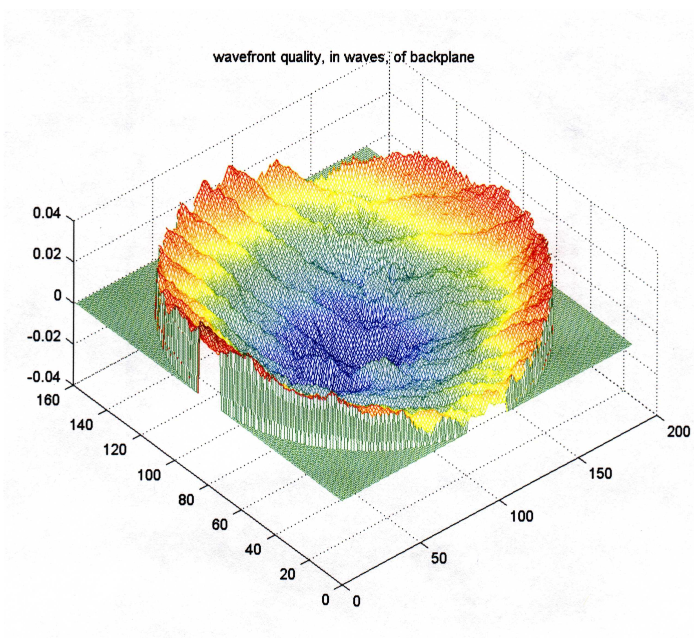


Figure 2: Measured reflected wavefront from the back-plane of the device

Once the Indium-Tin-Oxide (ITO) electrical contact layers were deposited and the transparent window and cell attached to the backplane, the device was filled with the LC material. The reflected wavefront from the functional device was then re-measured the results of these measurements are shown in Fig. 3. The peak-to-valley wavefront value in the functional device

was λ/2. The reduced quality of the wavefront can be attributed to the many production steps and new deposited layers in between in making a liquid crystal device. However, the overall quality is still appropriate for its use in wavefront control, especially if one keeps in mind the elevated number of corrective elements in this device and the possibility of removing static aberrations by the device itself. The main feature of the wavefront aberration is astigmatism, as expected, due to the pressure induced stress gradients induced by way that the device has been filled.

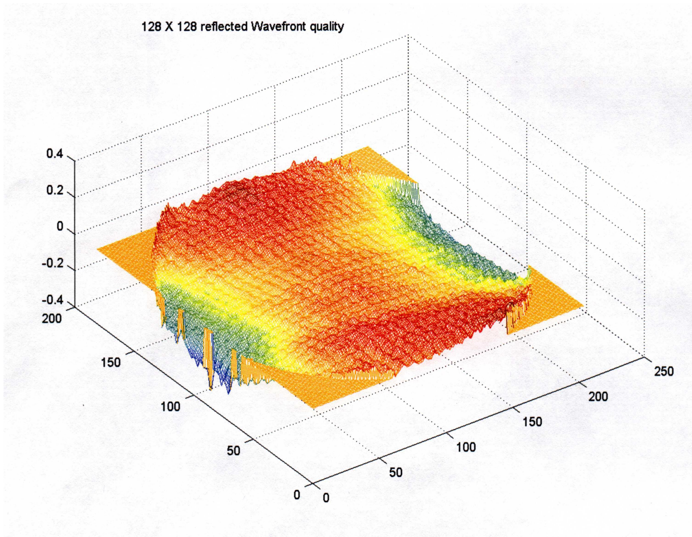


Figure 3: Measured reflected wavefront from the overall device.

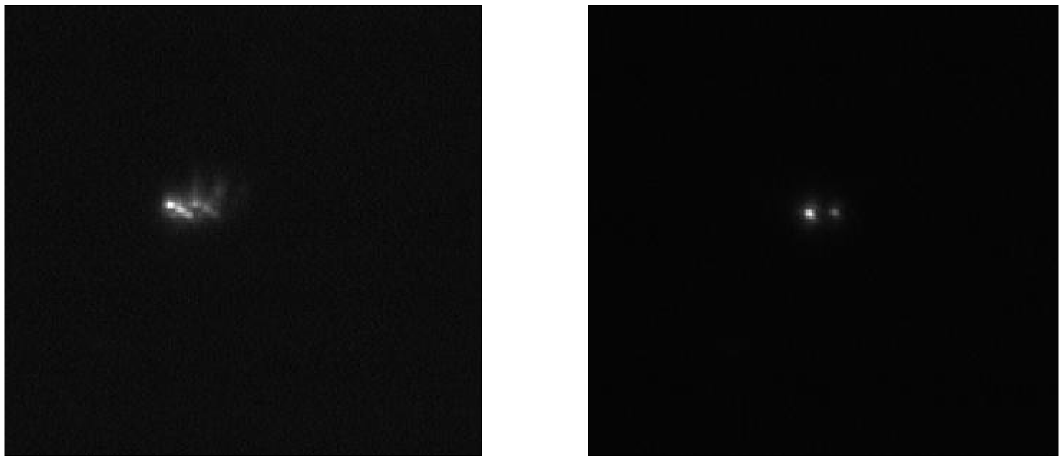
3. Field experiment of LC AO.

In order to obtain a fast frame-rate for a device that can be used in a real time closed loop AO system, and at the same time maintain a useful throw (few waves at visible wavelengths) as shown by eq. 1, it is necessary to use dual frequency nematic materials. The dual frequency nature of nematic materials is well understood and established, however, most commercially available nematic materials have a crossover frequency in the MHz region, this rends them not useful for our applications. Few materials were synthesized with a crossover frequency in the KHz region. One of such materials, LC-1001, developed by a Russian firm, was used by Meadowlark Optics to develop a device for AO applications. The device has 127 independently activated elements (pixels) with a clear aperture of 15 mm. The device has a reflective back-plane and sandwiched between the LC cell and the back-plane there is a quarter wave-plate. This allows to modulate unpolarized light. An experimental set up using a conventional Shack-Hartman wavefront sensor and a control loop and reconstructor based on a standard PC was extensively tested in the laboratory [15]. The system was then moved to the Air Force facility in Maui where we closed the loop on various objects. The telescope used was the 3.67 meter Advanced Electro-Optical System (AEOS), with a pupil mask of one meter on the side of the secondary obscuration. The pupil mask was necessary due to the limited number of corrective elements available on the device. The number of corrective elements in an AO system is given by:

$$N \propto \left(\frac{D}{r_0}\right)^2$$

where D is the diameter of the pupil to be corrected and r_0 is the coherence diameter of the atmosphere, or Fried's parameter. This parameter can be thought as the size of a telescope that will only see a global tilt as wavefront aberration, and it is a measurement of the atmospheric turbulence at the specific site at a specific time. By definition r_0 is highly statistical in nature, and changes dynamically with time and location. Typical values for this parameter range between 10 and 15 cm in good conditions, in a good astronomical site, at visible wavelengths. Considering that the LC device corrective elements are "piston only" the number of effective elements available is reduced by a factor of roughly 1/3. This gives a good match between the available number of corrective elements and a pupil of 1 meter with an r_0 of 15 cm, thus the choice of the mask.

An example of the closed loop results from one of our runs is shown in Fig. 4. Here a close binary star, β Delphini, is imaged without the use of AO. The two companions are blurred together, whilst with the AO system on, the two components are well separated and both visible.



(a) (b)

Figure 4: Single frame image of the binary star β Delphini. (a) open loop frame, (b) closed loop frame.

The instantaneous Strehl ratio, i.e. the ratio of the peak intensity of the aberrated Point Spread Function (PSF) of the system over the aberrated PSF, was of 20% in open loop and ~40% in closed loop.

4. Conclusions

In this paper we have presented some preliminary results of the characterization of the largest liquid crystal device presently available for use in adaptive and active optics. The device was delivered only few months ago as such the results presented here are limited. However, it is already obvious that due to the high number of corrective elements, more than 10,000, this device can definitely be used for high-resolution wavefront control. At this point in time we do not yet have a good dynamical characterization to address the issue of refresh rate and closed loop operations. Even though the device may have relatively slow dynamical behavior, it will still be very useful for slowly varying wavefront aberration control, similar to that encountered due to gravity sagging of a thin primary mirror, thermal fluctuations, etc often corrected using active optics. We have also presented results of closed loop operations of a liquid crystal device in a field experiment. These technical progress indicate in a convincing way that liquid crystal device can indeed be used as components for AO systems.

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